

Evidence for vortex staircases in the whole angular range due to competing correlated pinning mechanisms

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We present measurements of the angular dependence of the irreversible magnetization of $\text{YBa}_2\text{Cu}_3\text{O}_7$ single crystals with columnar defects inclined with respect to the c axis. At high fields a sharp maximum centered at the tracks direction is observed. At low fields we identify a lock-in phase characterized by an angle-independent pinning strength and observe an angular shift of the peak towards the c axis that originates in the misalignment between vortices and applied field in anisotropic materials. The interplay among columnar defects, twins, and intrinsic pinning by the ab planes generates a variety of staircase structures. We show that correlated pinning dominates for all orientations of the applied field. [S0163-1829(99)09417-5]

A difficult aspect of the study of vortex dynamics in high-temperature superconductors in the presence of correlated disorder is the determination of flux structures for applied fields tilted with respect to the pinning potential. As three-dimensional vortex configurations cannot be directly observed, our knowledge is mostly based on the analysis of the angular dependence of magnetization, susceptibility, or transport data.¹⁻¹¹

According to theoretical models,^{12,13} when the angle between the applied field \mathbf{H} and the defects is smaller than the lock-in angle φ_L vortices remain locked into the defects thus producing a transverse Meissner effect. For tilt angles larger than φ_L and smaller than a trapping angle φ_T , vortices form staircases with segments pinned into different defects and connected by unpinned or weakly pinned kinks. Beyond φ_T , vortices will be straight and take the direction of the applied field, thus being unaffected by the correlated nature of the pinning. In principle, this picture should apply with minor differences to twins, columnar defects, and intrinsic pinning.¹³

Many experiments have confirmed the directional pinning due to columnar defects, twins, and Cu-O planes.¹⁻¹¹ Evidence for a locked-in phase arises from the observation of the transverse Meissner effect,¹⁰ but a quantitative determination of $\varphi_L(H, T)$ for columnar defects had not been done until now. The introduction of columnar defects inclined with respect to the crystallographic axis has been used^{1,6-8,10,11} to discriminate their pinning effects from those due to twin boundaries, and from anisotropy effects. However, the vortex staircase configurations resulting from the combined effect of the various correlated structures had not yet been explored in detail.

In this work we report studies of the vortex pinning in $\text{YBa}_2\text{Cu}_3\text{O}_7$ crystals with inclined columnar defects, for the whole range of field orientations. This allows us to determine the misalignment between the applied and internal fields due to anisotropy, as well as to identify the angular range of influence of each correlated pinning structure. We present the first determination of the lock-in angle of tracks using irreversible magnetization.

The crystal used in this study was grown by the self-flux method,¹⁴ and has dimensions $\sim 200 \times 600 \times 8.5 \mu\text{m}^3$. Columnar defects at an angle $\Theta_D \approx 32^\circ$ from the c axis and a density corresponding to a matching field $B_\Phi = 3 \text{ T}$ were introduced by irradiation with 315 MeV Au^{23+} ions at the Tandem accelerator (Buenos Aires, Argentina).

dc magnetization \mathbf{M} was measured in a Quantum Design superconducting quantum interference device magnetometer with two sets of pickup coils, and both the longitudinal (M_l , parallel to \mathbf{H}) and transverse (M_t , perpendicular to \mathbf{H}) components were recorded. The sample could be rotated *in situ* around an axis perpendicular to \mathbf{H} using a homemade device.¹⁵ The angle Θ between the normal to the crystal (that coincides with the c axis) and \mathbf{H} was determined from the angular dependence of the response in the Meissner state. The details of this procedure, that give us an absolute accuracy $\sim 1^\circ$, and relative variations between adjacent angles better than 0.2° , are described elsewhere.¹⁵ Careful alignment of the rotation axis with the normal to the plane of irradiation ensures that the condition $\mathbf{H} \parallel \text{tracks}$ can be achieved within $\sim 1^\circ$.

Isothermal magnetization loops $M_l(H)$ and $M_t(H)$ were recorded at fixed Θ . The sample was then rotated, warmed up above T_c , and cooled down in zero field to start a new run. In this way, the initial Meissner response was recorded for each angle. We use the widths of the hysteresis $\Delta M_l(H)$ and $\Delta M_t(H)$ to calculate the modulus $M_i = \frac{1}{2} \sqrt{\Delta M_l^2 + \Delta M_t^2}$ and direction of the irreversible magnetization vector \mathbf{M}_i . It is known that in thin samples \mathbf{M}_i is normal to the surface due to geometrical constraints,^{15,16} except above a critical angle $\sim 87^\circ$ for the geometry of our crystal. We have confirmed that $\mathbf{M}_i \parallel c$ within 1° , for all $\Theta < 85^\circ$.

From now on we analyze the modulus M_i as a function of T , H , and Θ . Figure 1 shows M_i versus Θ at two temperatures. For clarity, only a few values of H are shown. According to the critical state Bean model, M_i is proportional to the screening current density J (which is lower than the critical current J_c due to thermal relaxation). The geometrical factor

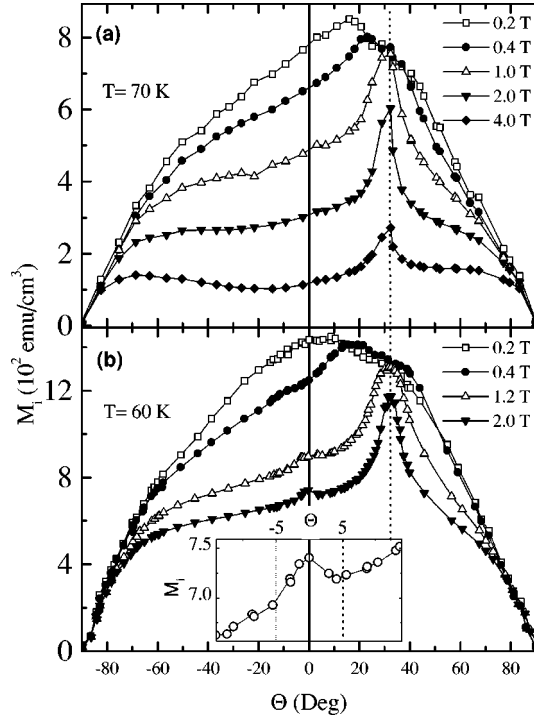


FIG. 1. Widths of the hysteresis loops $M_i(H)$ as a function of the applied field angle Θ for several fields, at temperatures (a) $T = 70$ K and (b) $T = 60$ K. The inset shows a blowup of the $H = 2$ T data near the c axis for $T = 60$ K. The units in the inset are the same of those of the main figure.

between M_i and J depends on Θ , but it is almost constant for Θ lower than the critical angle. Thus the vertical axis in Fig. 1 is directly proportional to J over almost all the angular range.

The most obvious feature of Fig. 1 is the asymmetry with respect to the c axis, which is due to the uniaxial pinning of the inclined tracks. At high fields ($H \geq 1$ T) we observe a large peak in the direction of the tracks $\Theta_D \approx 32^\circ$. For $H < 1$ T the peak becomes broader and progressively shifts away from the tracks in the direction of the c axis as H decreases. The shift decreases with increasing T as shown in Fig. 2, where the angle Θ_{\max} of the maximum in M_i is plot-

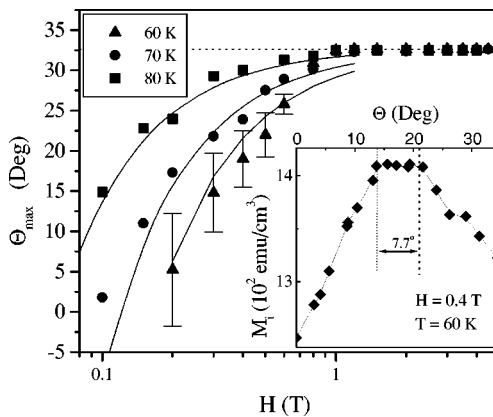


FIG. 2. Angle Θ_{\max} of the maximum in $M_i(H)$ as a function of H for three temperatures. The solid lines are fits to Eq. (1) (see text). Bars mark the width of the plateau. Inset: $M_i(H)$ versus Θ_{\max} in the region of the plateau for $H = 0.4$ T and $T = 60$ K.

ted as a function of H for three temperatures. The inset of Fig. 2 shows a blowup of the data of Fig. 1 for $H = 0.4$ T and $T = 60$ K. This curve exhibits the second main characteristic of the low-field results, namely the existence of a plateau in $M_i(\Theta)$ (We define Θ_{\max} as the center of the plateau).

We first discuss the origin of the shift. Maximum pinning is expected to occur when the tracks are aligned with the direction that the vortices would have in the absence of pinning. For an anisotropic material, such direction does not coincide with \mathbf{H} . If Θ_B is the angle between the equilibrium induction field \mathbf{B} (which represents the vortex direction) and the c axis, minimization of the free energy for $H_{c1}^c \ll H \ll H_{c2}^c$ gives¹³

$$\sin(\Theta_B - \Theta) \approx \frac{H_{c1}^c(1 - \varepsilon^2)}{2H \ln \kappa} \frac{\sin \Theta_B \cos \Theta_B}{\varepsilon(\Theta_B)} \ln \left(\frac{H_{c2}^c(\Theta_B)}{B} \right), \quad (1)$$

where $H_{c2}^c(\Theta_B) = H_{c2}^c / \varepsilon(\Theta_B)$. Here H_{c1}^c and H_{c2}^c are the lower and upper c axis critical fields, ε is the anisotropy and $\varepsilon(\theta) = (\cos^2 \theta + \varepsilon^2 \sin^2 \theta)^{1/2}$. For $\varepsilon < 1$ vortices tilt towards the ab plane. When $\Theta = \Theta_D$ we have $\Theta_B > \Theta_D$ and the optimum pinning situation is not satisfied. Instead, maximum M_i occurs at the vortex-track alignment condition $\Theta_B = \Theta_D$. This corresponds to an applied field angle $\Theta_{\max} < \Theta_D$ that can be calculated from Eq. 1 by setting $\Theta_B = \Theta_D \approx 32^\circ$. (Within this picture the peak cannot occur at $\Theta < 0$, thus the negative values of Θ_{\max} given by Eq. 1 at low H are unphysical, and Θ_{\max} must approach zero as $H \rightarrow 0$.)

The solid lines in Fig. 2 are fits to Eq. 1 with fixed parameters¹³ $\varepsilon = 1/7$ and $H_{c2}^c(T) = 1.6$ T/K $\times (T_c - T)$ (the fits are not very sensitive to any of them). Using $H_{c1}^c(T)/2 \ln \kappa = \Phi_0/8\pi\lambda_{ab}^2(T)$ and $\lambda_{ab}^2(T) \approx \lambda_{ab}^2(0)(1 - T/T_c)^{-1}$, we obtain a good fit to the data as a function of field and temperature by setting only one free parameter, $\lambda_{ab}(0) \approx 500$ Å. Although this value is significantly smaller than the accepted value¹³ (~ 1400 Å), we note that this is a very simplified model, where additional effects such as demagnetizing factors, geometrical barriers, or deviations from Ginzburg-Landau theory are not included. We nevertheless consider that it captures the basic physics. We note that Zhukov *et al.*¹⁰ have reported lock-in angles for twin boundaries in $\text{YBa}_2\text{Cu}_3\text{O}_7$ crystals that imply an H_{c1}^c about five times larger than the usual values, a result suggestively similar to our case. The quantitative aspects of these effects clearly require further investigation.

We now return to the plateau seen in the inset of Fig. 2. The constancy of $M_i(\Theta)$ indicates that the pinning energy remains constant and equal to the value at the alignment condition $\Theta_B = \Theta_D$. This behavior is a fingerprint of the lock-in phase.¹² To determine the range of the plateau with good accuracy ($\sim 1^\circ$), we have measured about one loop per degree at $T = 60$ K for $10^\circ < \Theta < 40^\circ$. The extension of the plateau in the H - Θ plane at 60 K is shown as bars in Fig. 2. Its width decreases approximately as H^{-1} , as expected¹² for φ_L , and for $H > 1$ T it becomes undetectable with our resolution. The decrease of M_i at the edges of the plateau is sharp, a result consistent with the appearance of kinks, which not only reduce J_c but also produce a faster relaxation.

When $|\Theta_B - \Theta_D| > \varphi_L$ vortices form staircases. Two questions arise here. First, which is the direction of the kinks that

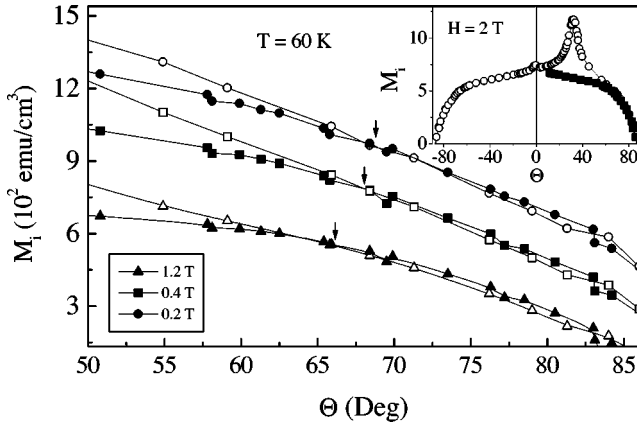


FIG. 3. Angular dependence of the irreversible magnetization $M_i(H)$ for three fields at $T = 60$ K. Open symbols: data for $\Theta > 0$. Solid symbols: data for $\Theta < 0$, reflected with respect to the c axis. Some of the curves were displaced vertically for clarity. The arrows indicate the angle Θ_{sym} beyond which the behavior is symmetric with respect to the c axis. The procedure of reflection of the data is sketched in the inset.

connect the pinned portions of the vortices? Second, do we observe evidence for a trapping angle φ_T ?

For $\Theta > \Theta_{\text{max}}$, there is a wide angular range in Fig. 1 in which $M_i(+\Theta) > M_i(-\Theta)$ for all H , i.e., pinning is stronger when H is closer to the tracks than in the crystallographically equivalent configuration in the opposite side. This asymmetry demonstrates that at the angle $+\Theta$ vortices form staircases, with segments trapped in the tracks. For $\Theta < \Theta_{\text{max}}$ we again observe asymmetry, $M_i(\Theta)$ crosses $\Theta = 0$ with positive slope, indicating that pinning decreases as H is tilted away from the tracks. We can conclude that staircases extend at least beyond the c axis into the $\Theta < 0$ region.

The angle θ_k between the kinks and the c axis can be calculated by minimization of the free energy.¹³ For simplicity, let's consider the case $H \gg H_{c1}^c$, where $\Theta_B = \Theta$ and the problem reduces to calculate the energy of one single vortex, as the other terms in the free-energy density are the same for all configurations.^{8,11} If L_p is the length of a pinned segment, and L_k the length of the kink (see sketch in Fig. 4), the line energy is $E \propto L_p \epsilon_p(\Theta_D) + L_k \epsilon_f(\theta_k)$, where $\epsilon_f(\theta_k) \approx \epsilon_0 \epsilon(\theta_k) [\ln \kappa + 0.5]$ and $\epsilon_p(\Theta_D) \approx \epsilon_0 \epsilon(\Theta_D) [\ln \kappa + \alpha_t]$ are the line energy for free and pinned vortices, respectively, ϵ_0 is the vortex energy scale and $\alpha_t < 0.5$ parametrizes the core pinning energy due to the tracks (smaller α_t implies stronger pinning). Minimizing E with respect to θ_k we obtain the two kink orientations, θ_k^- for $\Theta < \Theta_D$ and θ_k^+ for $\Theta > \Theta_D$.

As the tracks are inclined, $|\theta_k^-|$ and $|\theta_k^+|$ are different. However, those angles are independent of Θ . As $|\Theta - \Theta_D|$ increases, θ_k^\pm remain constant while L_p decreases and the number of kinks increases, consequently the pinning energy lowers. This accounts for an M_i that decreases as we move away from the tracks. In particular, for $\Theta = \theta_k^\pm$ vortices become straight ($L_p = 0$), thus $\varphi_T^\pm = |\theta_k^\pm - \Theta_D|$ are the trapping angles in both directions. In general θ_k^\pm must be obtained numerically, but for $\epsilon \tan \theta_k \ll 1$ and $\epsilon \tan \Theta_D \ll 1$ we obtain

$$\tan \theta_k^\pm \approx \tan \Theta_D \pm \frac{1}{\epsilon} \frac{1 - 2\alpha_t}{\ln \kappa + 0.5}. \quad (2)$$

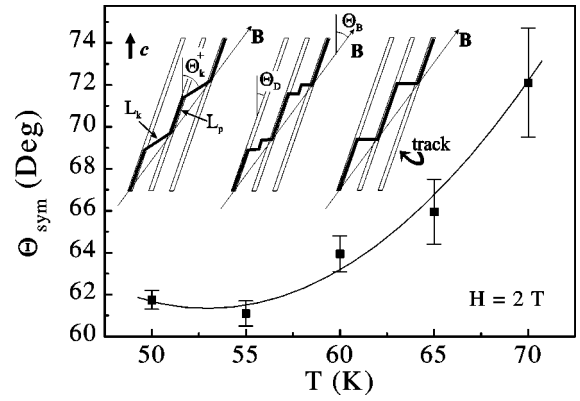


FIG. 4. Temperature dependence of Θ_{sym} (see Fig. 3). The solid line is a guide to the eye. The sketches show the possible vortex staircases for $\Theta > \Theta_D$.

Equation (2) adequately describes the main features of the asymmetric region in Fig. 1, and for $\Theta_D = 0$ it coincides with the usual estimates^{12,13} of φ_T .

There is, however, an important missing ingredient in the standard description presented above, namely the existence of twins and Cu-O layers, which are additional sources of correlated pinning. This raises the possibility that vortices may simultaneously adjust to more than one of them, forming different types of staircases.

Pinning by twin boundaries is visible in Fig. 1 as an additional peak centered at the c axis for $H = 2$ T and $T = 60$ K. A blowup of that peak is shown in the inset. We observe this maximum for $H \geq 1$ T. The width of this peak, $\sim 5^\circ$, is in the typical range of reported trapping angles for twins.^{3-5,9,10} On the other hand, the fact that the peak is mounted over an inclined background implies that vortices are also trapped by the tracks. Thus vortices in this angular range contain segments both in the tracks and in the twins. These two types of segments are enough to build up the staircases for $\Theta > 0$, but for $\Theta < 0$ a third group of inclined kinks with $\theta_k < 0$ must exist in order to have vortices parallel to \mathbf{H} .

Another fact to be considered is that the asymmetry in $M_i(\Theta)$ disappears as Θ approaches the ab planes. This is illustrated in Fig. 3, where M_i data for $-|\Theta|$ was reflected along the c axis and superimposed to the results for $+|\Theta|$. There is a well-defined angle Θ_{sym} beyond which $M_i(\Theta)$ recovers the symmetry with respect to the c axis. We have also found that Θ_{sym} is only weakly dependent on H .

One possible interpretation is that for $\Theta > \Theta_{\text{sym}}$ staircases disappear, i.e., that $\Theta_{\text{sym}} = \theta_k^+$ and we are determining $\varphi_T^+ = \Theta_{\text{sym}} - \Theta_D$. However, this is inconsistent with our experimental results. Indeed, φ_T^+ should decrease with T , and this decrease should be particularly strong above the depinning temperature¹⁷ $T_{dp} \sim 40$ K due to the reduction of the pinning energy by entropic smearing effects.¹² This expectation is in sharp contrast with the observed increase of Θ_{sym} with temperature, which is shown in Fig. 4 for $H = 2$ T. Thus the interpretation of Θ_{sym} as a measure of the trapping angle is ruled out. Moreover, if in a certain angular range vortices were not forming staircases, pinning could be described by a scalar disorder strength, then at high fields $M_i(\Theta)$ should follow the anisotropy scaling law¹⁸ $M_i(H, \Theta)$

$=M_i[\varepsilon(\Theta)H]$. Consistently, we do not observe such scaling in any angular range.

Our alternative interpretation is that, as \mathbf{H} approaches the ab planes, the kinks become trapped by the intrinsic pinning. This idea has been used by Hardy *et al.*⁸ to explain that the J_c at low T in the very anisotropic Bi and Tl compounds with tracks at $\Theta_D = 45^\circ$ was the same for H either parallel or normal to them. Our situation is somewhat different, as we are comparing two configurations both having kinks.

We first note that, according to Eq. (2), θ_k^\pm cannot be exactly 90° for finite ε , thus the intrinsic pinning must be incorporated into the model by assigning a lower energy to kinks in the ab planes. Vortices may now form structures consisting of segments trapped in the columns connected by segments trapped in the ab planes, or alternatively an inclined kink may transform into a staircase of smaller kinks connecting segments in the planes (see sketches in Fig. 4). We should now compare the energy of the new configurations with that containing kinks at angles θ_k^\pm . This is equivalent to figure out whether the kinks at θ_k^\pm lay within the trapping regime for the planes or not. The problem with this analysis is that, as θ_k^\pm are independent of Θ , one of the two possibilities (either inclined or trapped kinks), will be the most favorable for all Θ . Thus this picture alone cannot explain the crossover from an asymmetric to a symmetric regime in $M_i(\Theta)$.

The key concept to be considered in this scenario is the dispersion in the pinning energy of the tracks. The angles θ_k^\pm depend on the pinning strength of the adjacent tracks [α_t in Eq. (2)], thus a dispersion in α_t implies a dispersion in θ_k^\pm . As Θ increases, it becomes larger than the smaller θ_k^\pm 's (that connect the weaker defects) and the corresponding kinks disappear. The vortices involved, however, do not become straight, but remain trapped by stronger pins connected by longer kinks with larger θ_k^\pm . This process goes on as Θ grows: the weaker tracks progressively become ineffective as the "local" θ_k is exceeded, and the distribution of θ_k^\pm shifts towards the ab planes. When a particular kink falls within the trapping angle of the planes, a switch to the

pinned-kink structure occurs. In this new picture, the gradual crossover to the symmetric regime as $|\Theta|$ increases takes place when most of the remaining kinks are pinned by the planes.

If kinks become locked, the total length of a vortex that is trapped inside columnar defects is the total length of a track, independent of Θ , and the total length of the kinks is $\propto \tan(|\Theta \pm \Theta_D|)$ for field orientations $\pm \Theta$, respectively. As $|\Theta|$ grows, the relative difference between the line energy in both orientations decreases, an effect that is reinforced by the small line energy of the kinks in the ab planes. If kinks are not locked but rather form staircases, taking into account that the trapping angle for the ab planes is small⁴ ($\sim 5^\circ$), the same argument still applies to a good approximation. The temperature dependence of Θ_{sym} is now easily explained by a faster decrease of the pinning of the ab planes with T as compared to the columnar defects.

Additional evidence in support of our description comes from transport measurements in the dc-flux transformer configuration. Recent results show that, in contrast with untwinned crystals, in the liquid phase in *twinned* YBa₂Cu₃O₇ crystals vortices remain correlated along the c axis for *all field orientations*.¹⁹ This suggests that, for all angles, vortices are composed solely of segments in the twins and in the ab planes.

In summary, we have shown that the combined effect of the three sources of correlated pinning must be taken into account to describe the vortex structure in samples with inclined columnar defects. We demonstrate that the lock-in phase exhibits an angle independent pinning strength, and show the decrease of the lock-in angle with field. Our results show that a variety of complex staircases are formed depending on the field orientation and strongly suggest that, at high temperatures, correlated structures dominate vortex pinning over random disorder in the whole angular range.

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